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LCA FOR AGRICULTURE

Determination of environmental impacts of antimicrobial usage for US Northern Great Plains swine-production facilities: a life-cycle assessment approach

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Abstract
Purpose This study used life-cycle assessment (LCA) methodology to examine the environmental effects associated with sub-therapeutic tylosin and chlortetracycline (CTC) antimicrobial use within US Northern Great Plains (NGP) swine-production facilities. Antimicrobial feed-additive use is widespread within this industry and is expected to play an integral role within future carbon-management strategies due to its ability to increase feed efficiency and control disease.
Materials and methods The LCA model system boundaries for this study were: (1) antimicrobial manufacturing; (2) feed manufacturing; (3) transport of antimicrobials to the feed-mill and completed feed to the swine-production facility; (4) electricity and propane use associated with swine-production operations; and (5) swine enteric and manure-storage and handling emissions. The functional unit is the growth life cycle of one head of swine from starter (7 kg) to finisher (111 kg market weight; "wean-to-finish") production stages. Environmental impacts considered include global warming, acidification and eutrophication, ecotoxicity, and fossil-fuel use following EcoIndicator 99 assessment methodology.
Results and discussion High-estimated energy requirements associated with CTC and tylosin manufacturing, coupled with the large transportation distances to the feed manufacturing and swine-production facilities increased climate change and ecotoxicity impacts compared with a no antimicrobial-use scenario. However, feeding CTC resulted in several local positive changes including increased feed utilization, lower producer costs due to shortened production times, and reduced manure greenhouse gas emissions. These positive changes in the local environment however did not offset negative global impacts associated with material manufacturing and transport for the specific scenarios analyzed. Increased use of renewable-energy sources for both swine and antimicrobial production resulted in net environmental enhancement.
Conclusions This study demonstrates both the beneficial and negative environmental aspects associated with sub-therapeutic antimicrobial within the swine-production industry, and provides swine producers and environmental practitioners with tangible alternatives for meeting both livestock-health management and future carbon-management constraints within a reduced-carbon-emission consumer and regulatory marketplace.

Keywords Antimicrobial use · Chlortetracycline · Climate change · Ecotoxicity · Swine production · Tylosin

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1 Introduction

The use of antimicrobial compounds within the animal-feeding industry during the past 50 years is both widespread and well documented. The most common of the

pharmacological drugs administered within the swine industry are those classified as tetracycline and bacitracin, both of which account for greater than 1.4 million kilograms of annual use within the animal-production industry (Mackie et al. 2006). When administered in low (sub-therapeutic) doses, antimicrobial compounds increase swine growth rate and feed efficiency, decrease mortality, and enhance reproductive performance (Cromwell 2002), while high (therapeutic) doses of the antimicrobial compounds treat swine diseases. About 70%–80% of all starter and grower feeds and 50%–60% of all finisher feeds blended and sold in the US contain antimicrobial compounds (Cromwell 2002; Dewey et al. 1999). Chlortetracycline (CTC) and tylosin account for >64% and >48% of antimicrobial compounds used within various stages (i.e., starter, grower, and finisher) of the swine industry, respectively (Sarmah et al. 2006; Dewey et al. 1999; USDA 2007).

Land spreading of manures is a common method used to recycle nutrients and organic matter back to crop-production areas. However, swine that have ingested feeds containing some antimicrobials can excrete up to 90% of the dose in urine and up to 75% of the dose in feces (Sarmah et al. 2006) due to the compounds' high water solubility. While both compounds have reported half-lives ranging from hours to days (Allaire et al. 2006; Clay et al. 2005), there have been numerous reports of CTC and tylosin or their associated metabolites within aged manure-handling systems (e.g., (Jindal et al. 2006; Masse et al. 2000; Kolz et al. 2005a, b)) and land applied soils (e.g., (Agerso et al. 2006; Grote et al. 2007; Halling-Sorensen et al. 2005; Kumar et al. 2005; Thiele-Bruhn 2003)). Land spreading of manure, therefore, must be done in an appropriate manner, as incidental antimicrobial discharges within surface and groundwater aquatic systems can occur, which highlights one of the environmental challenges associated with widespread antimicrobial use within the agricultural sector.

There is little information regarding the life-cycle environmental impacts associated with antimicrobial use within the animal-feeding industry. US swine production currently is undergoing close scrutiny to improve estimates of its carbon footprint (Stokes 2009). Antimicrobial use certainly will have an integral role within these future carbon-management strategies due to its ability to increase feed efficiency and control disease. The purpose of this study was to determine the life-cycle impact associated with antimicrobial use (CTC and tylosin) within the US Northern Great Plains (NGP) swine-production industry. The NGP region accounts for 13% of the US market (USDA 2009), and generally has greater heating and ventilation requirements compared with other US swine-production regions. Specifically, life-cycle environmental impacts were determined for all significant processes and phases associated with NGP swine-production facility operations, and CTC and tylosin manufacturing and use. A scenario analysis was performed to determine whether outcomes could be changed and associated environmental impacts could be reduced using modifications to modeled processes.

2 Methods

2.1 Goal

The project goal was to calculate and compare the environmental impacts associated with administering sub-therapeutic doses of antimicrobial compounds within a modern Northern Great Plains US swine-production facility. Three distinct production scenarios were modeled: one with a facility not administering antimicrobial compounds, and two where either CTC or tylosin was administered at commonly prescribed sub-therapeutic doses.

2.2 Functional unit

The study focuses on the growth life cycle of one head of swine from starter (7 kg) to finisher (market weight of 111 kg; "wean-to-finish") stages of production. The nursery and gestation-facility phases were excluded from analysis since these stages typically are separate entities for most modern swine-production operations (See 2008). All LCA model data and results were normalized to a per-head-of-swine unit for the basis of evaluation.

2.3 System boundaries

The system boundaries for this study consisted of the following antimicrobial manufacturing, feed manufacturing and production facility operational stages as shown in Fig. 1. It should be noted that the system boundaries do not account for abattoir or other post production supply–chain processes, or upstream feedstuff production and associated feedstuff transport to a regional feed-mill. Instead, the system boundaries allow the impacts directly associated with antimicrobial use to be effectively determined.

3 Inventory analysis

The LCA model was developed using SimaPro7.1 LCA modeling software (PRé Consultants, Netherlands) following ISO 14040 protocols (2006). Three operation scenarios (tylosin, CTC, and no antimicrobial use) were represented by modeling five distinct sub-processes associated with

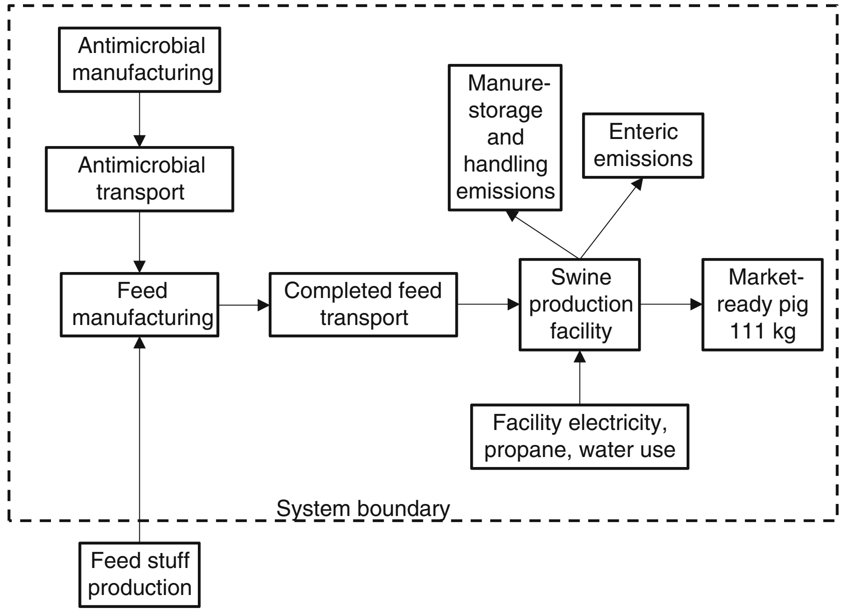

Fig. 1 LCA model system boundaries for the study indicated by the *dashed line*. Model input processes indicated with *rectangular boxes*. Crop-production attributes are not changed when antimicrobial compounds are used; therefore, boundaries associated with feeds began at the feed-manufacturing stage

typical swine-production facility operations: (1) *Antimicrobial manufacturing*: production of antimicrobial compounds, including related energy and raw materials; (2) *Feed manufacturing*: energy associated with corn (*Zea mays*) and soybean (*Glycine max*) feed manufacturing and milling; (3) *Transportation*: transport of antimicrobials to the feed-mill and completed feed to the swine-production facility; (4) *Electricity and propane use*: heating and electricity requirements associated with the swine-production facility operations; and (5) *Enteric and manure-storage and handling emissions*: both metabolic and manure-storage and handling emissions associated with swine-production facility operations.

Model input parameters were estimated through discussions with professional swine producers who regularly administer sub-therapeutic doses of feed-based antimicrobial compounds, site visits from two US NGP swine-production facilities, consultation of operations reference materials (See 2008) and supporting literature, and interviews with CTC and tylosin manufacturers. Energy data and quantities for each stage were normalized to the per-head-of-swine functional unit. Tangential allocation data related to specific material processes were obtained from the EcoInvent database v 2.1 (Zurich, Switzerland), unless otherwise specified below. Uncertainty associated with the impacts was determined by Monte Carlo analysis assuming normal distribution with a variance not exceeding 1.5 for up to 1,000 model runs, and presented as 95% confidence interval associated with mean impact value. A random value was chosen for each network flow, with the resulting range of all calculations providing a specific degree of uncertainty.

Specific sub-process input parameters for the LCA model were estimated as follows in section 3.1.

3.1 Antimicrobial production

Specifics regarding the manufacturing of CTC and tylosin were difficult to estimate due to the proprietary nature of these industrial processes (R. Butler, Elanco Animal Health, pers. comm.; T. Wolff, Alpharma Inc., personal communication) and the data availability was generally considered incomplete and inhomogeneous (e.g., similar problems encountered by Nielsen et al. (2007)). As a result, the antimicrobial LCA-input data were based upon a combination of theoretical chemical engineering principles, consultations with industry personnel, US Patent and Trademark Office information, and selection of a proxy chemical (acetic acid) from the EcoInvent database. Both CTC and tylosin are manufactured using large-scale, energy-intensive fermentation-batch processes (McCormick et al. 1958; Caltrider and Hayes 1969; Biffi et al. 1954); however, the organic composition of the medium, inoculums, and other specific constituents are proprietary and vary depending on the specific manufacturing process and ingredients used. Therefore, acetic acid production using the Monsanto process where carbon monoxide reacts with methanol under the influence of a rhodium complex catalyst at 180°C and pressures of 3–4 MPa was used as proxy reaction to evaluate both CTC and tylosin manufacturing processes. To account for high-energy use associated with the fermentation, recovery, and separation of enzymes from the biomass, and residuals treatment, an additional 1.0 MJ energy requirement per 1.0 g finished product (for both CTC and tylosin) was included within the model, providing a reasonable estimate of material and energy consumption associated with antimicrobial production (T. Menkhaus, South Dakota School of Mines and Technology, personal communication). CTC and tylosin use

were normalized to consumption rates based upon manufacturers' recommendations (K. Hoursche, CHS Nutrition, personal communication) and general feed practice (Table 1). The energy provided for antimicrobial production was based upon specific US state energy portfolios; i.e., Iowa for CTC production and Indiana for tylosin production (US-EIA 2010). Table 2 summarizes the regional energy portfolios normalized per head of swine.

3.2 Transportation of antimicrobials to feed manufacturing facility

Antimicrobial compound use in the US generally involves overland shipping to a regional feed manufacturing facility, where the additives are mechanically milled with the feed at prescribed doses (K. Hoursche, personal communication). The antimicrobial transport process was calculated by multiplying the mass of antimicrobial compound transported for each scenario by the distance from the production facility to the feed-mixing facility, resulting in mass distance (kg×km) (see Table 1). Mode of transport was assumed to be a 16-ton-capacity diesel truck with a 100% load factor. CTC was assumed to be shipped 370 km from Eagle Grove, Iowa (T. Wolff, pers. comm.) to Sioux Falls, South Dakota (feed-manufacturing location), while tylosin was assumed to be shipped 1,145 km from Clinton, Indiana (R. Butler, personal communication).

3.3 Feed manufacturing

A typical US NGP swine-production facility utilizes a blended feed comprised primarily of a corn:soybean ratio ranging from 60:25 to 83:10 (wet weight corn/soybean meal) depending on specific caloric,protein, and nutritional requirements (Table 3). Extraneous feed components constituting a total of <15% by mass of the administered feed (excluding the antimicrobial compounds; e.g., lactose, animal protein, cereal meal) were not accounted for within the LCA model; only corn and soymeal and the requisite antimicrobial dose were included. The exclusion of lactose and other animal protein products likely results in underestimating feed-associated LCA impacts due to their presumably significant environmental burdens. The quantity of feed, normalized per head of swine, was determined for each of the three swine-production stages: starter, grower, and finisher. Starter swine were categorized by a 15.6-kg weight gain (7 to 22.6 kg), grower swine were categorized by a 22.7-kg weight gain (22.6 to 45.3 kg), and finisher swine were categorized by a 65.7-kg weight gain (45.3 to 111 kg) (See 2008) (Table 4). The requisite mass of feed for each stage was calculated based upon feed/gain ratios from Cromwell (2002) and summarized in Table 5. The feed/gain ratios were adjusted depending on growth stage and antimicrobial usage.

CTC and tylosin doses were based on manufacturer recommendations, where CTC was administered at 0.111 kg per swine head, and tylosin was administered at 0.138 kg per swine head throughout the lifespan of the swine within the facility (K. Hoursche, personal communication).

Estimates of energy requirements for milling corn and soybean meal were based upon consultations with industry personal (K. Hoursche, personal communication) and normalized to each of the feed scenarios modeled (Table 6). The feed-manufacturing facility was assumed to be located in Sioux Falls, South Dakota, and electricity-source contributions for this location were calculated using energy portfolios representing mean South Dakota electricity generation (US-EIA 2010) (Table 7). For South Dakota, hydroelectric power constitutes the greatest source of electricity production (66%), followed by coal power (31%).

3.4 Completed-feed transport

Transportation input allocations (kg×km) were determined based upon mass of feed hauled and transport distance from the feed-manufacturing facility to the swine producer (see Table 1). A 16-ton-capacity diesel truck with a 50% load factor (empty return) was the assumed mode of transport. The feed-manufacturing facility was assumed to be located in Sioux Falls, South Dakota, while the swine-production facility was assumed to be located 96 km from the feed-

Table 1 Transportation data associated with feed-manufacturing and antimicrobial production energy allocations normalized per-head-of-swine life cycle for the three baseline scenarios

Scenario	Mass of feed meal with antimicrobials (kg)	Mass of antimicrobial administered (kg)	Distance from antimicrobial production to feed manufacturing facility (km)	Distance from feed manufacturing to swine production (km)	Mass for distance transported (kg km)	Antimicrobial production energy (MJ)
No antimicrobial use	NA	0.000	NA	96	30,569.8	0.0
CTC use	308.5	0.111	370	96	29,661.3	110.6
Tylosin use	308.5	0.138	1145	96	29,777.9	137.7

Table 2 Specific US state energy-production portfolios (Iowa for CTC, Indiana for tylosin) (US-EIA 2010) and total antimicrobial manufacturing energy-demand normalized per-head-of-swine life cycle, associated with the production of CTC and tylosin

Energy source	CTC production energy porfolio (Iowa) (%)	CTC production energy (MJ)	Tylosin production energy porfolio Indiana) (%)	Tylosin production energy (MJ)
Petroleum-fired	0.2	0.2	0.1	0.2
Hydroelectric	2.3	2.5	0.5	0.7
Natural gas	3.0	3.3	3.0	4.1
Nuclear	9.9	11.0	0.0	0.0
Other renewables	10.2	11.3	0.9	1.3
Coal-fired	74.4	82.4	95.4	131.4
Total	100.0	110.7	100.0	137.7

manufacturing facility, in Brookings, South Dakota. Transport distances assumed are common for typical NGP operations where a feed-mill may service several regional production facilities.

3.5 Swine-facility electricity and propane use

Total weight gain per head of swine was determined based upon methodology presented in Cromwell (2002) (see Table 6). Model calculations considered whether or not antimicrobials were administered for each of the facility stages. Energy requirements for facility propane heating, cooling, feed-auger operation, and lighting were estimated using data obtained during two facility site visits and from K. Hoursche (personal communication). Data was normalized per head of swine based upon consumption and swine life-cycle rates for each of the three scenarios (see Table 6).

3.6 Swine enteric and manure-storage and handling emissions

Two types of gaseous emissions were included within the model: swine enteric emissions (CH_4, CO_2, NH_3, and N_2O) and manure-storage emissions (CH_4 and CO_2). It was assumed that swine enteric emissions (volume of gas per unit mass of swine) were constant during the entire life cycle and independent of antimicrobial use (Table 8); although antimicrobials may presumably alter intestinal microbial populations impacting the volume and composition of enteric emissions. Enteric emissions were determined following similar protocols based upon CH_4, NH_3, N_2O (Dalgaard et al. 2006), and CO_2 (Dong et al. 2007) emission data.

The volume of CO_2 and CH_4 for manure-storage emissions varied by treatment. Estimated fluxes were based upon results of Stone et al. (2009), with similar emissions from manure of the no antimicrobial-use and tylosin treatments, while 28.4% and 27.8% reduction of CO_2 and CH_4, respectively, occurred when using CTC. NH_3 and N_2O emission rates were based upon Dalgaard et al. (2006) and were determined by normalizing the kilograms of gas emitted per kg weight gained and multiplying by the total kg weight gained over the swine life-cycle. Specific volatile suspended solid concentrations per liter of manure obtained from Stone et al. (2009) were normalized to the estimated volume of manure excreted (1.725 l day^{-1}), manure specific gravity, and swine life-cycle duration for the determination of total gas mass of the three model scenarios (see Table 8).

3.7 LCA inputs not utilized

Several process factors were not utilized as input data since their attributes were assumed unchanging regardless of

Table 3 Summary of corn, soybean and other feedstuff constituents by mass for starter, grower, and finisher feed stages, as recommended by K. Hoursche (personal communication)

Stage	Corn (%)	Soybean (%)	Other constituents not included (top three by %)
Starter feed	59.5	25.0	Lactose (5.0%)
			Cereal meal (2.5%)
			Fat, animal-stab (1.4%)
Grower feed	73.7	20.3	Meat and bone-pork (2.5%)
			Fat, animal-stab (1.5%)
			Calcium carbonate (0.9%)
Finisher feed	83.5	9.8	Meat and bone-pork (4.6%)
			Fat, animal-stab (1.0%)
			Calcium carbonate (0.7%)

Table 4 Feed requirements for one swine life cycle normalized per-head-of-swine life cycle for the three baseline scenarios

Scenario	Stage	Weight gain (kg)	Feed/weight gain (kg)/(kg)	Daily gain (kg)	Total days/scenario
No antimicrobial use	Starter	15.6	2.28	0.39	173.7
	Grower	22.7	2.91	0.59	
	Finisher	65.7	3.30	0.69	
CTC use	Starter	15.6	2.13	0.45	160.3
	Grower	22.7	2.78	0.66	
	Finisher	65.7	3.23	0.72	
Tylosin use	Starter	15.6	2.13	0.45	160.3
	Grower	22.7	2.78	0.66	
	Finisher	65.7	3.23	0.72	

antimicrobial compound use. For simplicity, water use for cooling and pen flushing or cleaning was ignored, although water volume would likely be less in the presence of antimicrobials due to reduced swine finishing time. Emission data associated with final product processing (i.e., processes after the final swine product leaves the production facility, such as rendering, packaging, transport to market, etc.) were considered beyond the scope of this study, and thus were not included within the LCA model. Furthermore, all processes associated with feedstuff production were not included within this study, primarily due to the lack of reliable, consistent, and region-specific data for crop growth, harvesting, and indirect land-use-associated impacts. The choice of feedstuff has been reported to have a significant influence on LCA environmental impacts (e.g., (Eriksson et al. 2005; Peters et al. 2010)), however feedstuff production was considered beyond this scope of this current study, and instead system boundaries began with feed manufacturing and milling (Fig. 1). Data associated with piglets weighing <7 kg also was excluded, as swine are not fed antimicrobials until weaned. Transportation of manure from the production-facility lagoon or holding tank to a local land-application site [generally within 16 km of the facility (Sarmah et al. 2006)], was assumed identical for all model scenarios, and thus was not considered.

3.8 Environmental impact assessment

The primary environmental issues for the three baseline scenarios under consideration were global warming, acidification and eutrophication, ecotoxicity, and fossil-fuel surplus. Impact-assessment characterization was based upon EcoIndicator 99 (hierarchist) v2.06 ((PRé Consultants, Netherlands) evaluation, where climate change was categorized under human-health impacts, ecotoxicity and acidification and eutrophication under ecosystem quality, and fossil-fuel surplus under resources. Climate-change impacts were determined based upon disability-adjusted life years (DALY) units following EcoIndicator 99 methodology, where DALY represents human-health damage based upon release of greenhouse gases that contribute to climate change (EcoIndicator-99 2000). Acidification and eutrophication impacts were calculated in units of potentially disappeared fraction (PDF m^2 y^{-1}), where both nitrogen and phosphorous releases to the environment were presumed to contribute equally to eutrophication, while nitrogen was responsible for acidification impacts (Lindors et al. 1995). Ecotoxicity was calculated in units of potentially affected fraction (PAF m^2 y^{-1}). The major contributors towards ecotoxicity are emissions of heavy metals such as lead, nickel, and zinc. Fossil-fuel surplus was determined as the MJ of surplus energy required throughout the entire swine lifecycle, where surplus fuel has been defined as the increased dependence of lower-quality fuels such as oil shale that future generations would be required to use as a result of current fossil-fuel consumption patterns (EcoIndicator-99 2000).

It should be noted that the actual environmental impacts associated with antimicrobial use may differ from those estimated within this study because, in practice, both compounds may be administered intermittently (which would overestimate impacts) (Dewey et al. 1999). Furthermore, a number of producers mill their feed on-site instead of using a regional feed-production facility; so, transportation impacts determined within this study would be overestimated for those specific operations.

Table 5 Feed and antimicrobial compound mass requirements for one swine life cycle normalized per-head-of-swine life cycle for the three baseline scenarios, as recommended by K. Hoursche (personal communication)

Scenario	Corn (kg)	Soymeal (kg)	Antimicrobial (kg)	Total feed (kg)
No antimicrobial use	250.8	32.8	–	283.6
CTC use	243.4	31.6	0.11	275.1
Tylosin use	243.4	31.6	0.14	275.2

3.9 Alternative-scenario analysis

A scenario analysis was performed to determine how changes associated with antimicrobial manufacturing or

Table 6 Energy requirements associated with feed manufacturing, and swine-production facility electricity and propane use normalized per-head-of-swine life cycle for the three baseline scenarios

Scenario	Feed milling energy (MJ)	Production facility energy (MJ)	Production facility heating (MJ propane)
No antimicrobial use	27.07	24.14	68.78
CTC use	26.23	22.28	63.48
Tylosin use	26.23	22.28	63.48

production-facility operations would modify potential impacts. Impact changes were determined in the following three scenarios: reducing the transportation distance from the feed-manufacturing facility to the swine-production facility, reducing the antimicrobial dosage, and changing the swine-production facility energy-allocation profile from a mean South Dakota profile to a mean US electricity allocation profile. For the scenario with a reduction in completed-feed transportation distance, it was assumed that the swine-production facility was located in Pipestone, MN, and the feed-manufacturing facility was located in Dell Rapids, SD, 37 km away by truck (59 km closer than in the baseline scenario). For the reduced antimicrobial dosage scenario, it was assumed that the production facility would administer a 50% lower dose in feed throughout the swine life cycle (ca. 10 mg kg^{-1} CTC and 44 mg kg^{-1} tylosin), thus reducing antimicrobial manufacturing, milling, and transportation impacts and decreasing the feed-utilization efficiency accordingly. For the average US electricity allocation scenario, the previously determined MJ demand for each baseline scenario was reallocated using the average US energy-allocation portfolio (see Table 7) (US-EIA 2010). Note that the antimicrobial manufacturing energy profile (see Table 2) was not changed in this scenario; only the feed-manufacturing and production facility energy profiles were revised, as changing these local energy-demand portfolios was considered more probable and realistic compared to changing energy sources associated with a large, centralized chemical manufacturing facility.

4 Baseline model results

4.1 Climate change

Feed manufacturing was consistently the greatest contributor towards climate change for all baseline scenarios, with the exception of tylosin production, which had the highest climate-change impacts of all processes in the study (8.86E−06 DALY; Fig. 2 and Table 9). Feed-manufacturing impacts were greatest for the no antimicrobial-use scenario (7.98E−06 DALY), whereas the antimicrobial-use scenarios resulted in a net reduction (displacement) of feed processed over the swine's life cycle due to increased feed utilization. For completed-feed transport and facility electricity generation and propane production climate-change impacts, no antimicrobial use resulted in slightly larger contributions towards climate change (9.69E−07 DALY for feed transport, 3.46E−06 DALY for electricity and propane) compared with CTC and tylosin use, and was directly attributed to the greater feed-utilization efficiency associated with antimicrobial use, resulting in less time for swine to reach market weight (see Fig. 2). Enteric and manure-storage emissions were similar for all scenarios (6.42E−06 DALY), which was surprising considering that CTC use would result in reduced CH_4 and CO_2 manure emissions; however, the relatively smaller volume of manure-storage emissions compared with swine metabolic emissions (see Table 8) resulted in an insignificant reduction (0.14% reduction) of net GHG emissions. For

Table 7 South Dakota energy portfolio used for feed manufacturing and swine-production facility operations, US average energy portfolio (US-EIA 2010), and South Dakota energy use normalized per-head-of-swine life cycle for the three baseline scenarios

Electricity source	South Dakota energy portfolio (%)	Production facility energy no antimicrobial use scenario (MJ)	Production facility energy CTC use scenario (MJ)	Production facility energy tylosin use scenario (MJ)	US average energy portfolio (%)
Hydroelectric	66.3	16.00	14.77	14.77	5.8
Coal-fired	31.0	7.48	6.90	6.90	48.5
Other renewables	2.6	0.63	0.58	0.58	3.1
Petroleum-fired	0.2	0.04	0.03	0.03	1.6
Nuclear	0.0	0.00	0.00	0.00	19.4
Natural gas-fired	0.0	0.00	0.00	0.00	21.6
Total	100.0	24.14	22.28	22.28	100.0

Table 8 Enteric and manure-storage emissions based upon volume of gas per unit mass of swine for the three baseline scenarios (Cromwell 2002)

Emission type	Scenario	CH_4 (g)	CO_2 (g)	NH_3 (g)	N_2O (g)
Enteric emissions	All scenarios	520.0	3,883.6	1,019.2	47.8
Manure emissions	No antimicrobial use	2.1	25.4		
	CTC	1.4	19.5		
	Tylosin	2.0	23.5		
Total emissions	No antimicrobial use	522.1	3,909.0	1,019.2	47.8
	CTC	521.4	3,903.0	1,019.2	47.8
	Tylosin	522.0	3,907.0	1,019.2	47.8

total climate-change impacts associated with each scenario (Fig. 3), no antimicrobial use resulted in the lowest climate-change impacts compared with the two antimicrobial-use scenarios, and this large difference was due to climate change related contributions associated with antimicrobial production and transport. The second highest climate-change impact was for CTC use (2.39E−05 DALY), while tylosin use resulted in the greatest impact (2.71E−05 DALY) and was due primarily to the greater net-energy consumption associated with tylosin manufacturing normalized per head of swine (Table 7) and the increased product-shipping distance compared to that of CTC.

4.2 Acidification and eutrophication

Antimicrobial use resulted in higher acidification- and eutrophication-impact scores (18.8 and 19.1 PDF m^2 y^{-1} for CTC and tylosin use, respectively) compared to no antimicrobial use (18.0 PDF m^2 y^{-1}; see Fig. 3 and Table 9). While relative acidification and eutrophication contributions for all scenarios were similar for feed-manufacturing and production-facility operations, the increased transportation and manufacturing-related impacts for antimicrobial

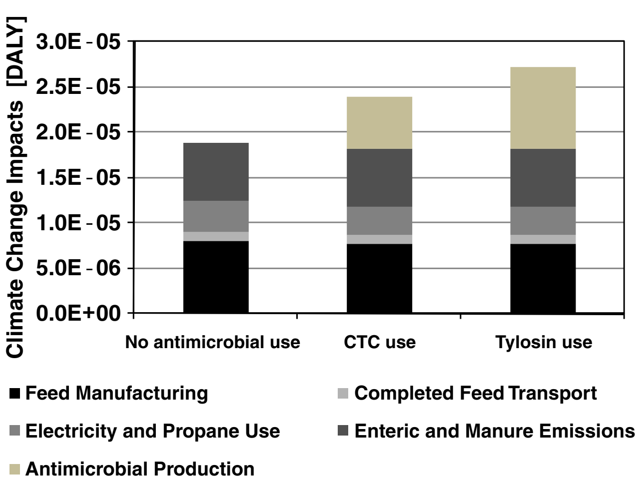

Fig. 2 Summary of the climate-change impacts (DALY) of five subprocesses for no antimicrobial-use, CTC-use, and tylosin-use scenerios

use resulted in higher overall impacts. Ammonia emissions consistently were the greatest contributor towards acidification and eutrophication for all scenarios (83–87% of the total contribution), signifying the importance of minimizing metabolic and manure-storage ammonia emissions to enhance ecosystem quality.

4.3 Ecotoxicity

Tylosin use resulted in the greatest ecotoxicity (1.14 PAF m^2 y^{-1}), while CTC impacts were moderately less (1.20 PAF m^2 y^{-1}; Fig. 4 and see Table 9). For the baseline conditions modeled, feed-manufacturing and facility electricity and propane-use impacts were relatively similar, accounting for approximately 49% and 19% of the total impacts, respectively. However, high impacts associated with antimicrobial production such as transportation and manufacturing increased ecotoxicity impacts of antimicrobial use compared with the no-use scenario.

4.4 Fossil-fuel surplus

Overall, there was little difference among the three scenarios, with all treatments having a fossil-fuel surplus between 100.6 and 104.2 MJ (Fig. 5). While CTC and tylosin use reduced impacts of feed manufacturing, swine-facility electricity and propane use, and completed-feed transport, the net fossil fuel-related impacts were similar for all scenarios modeled. Overall, fossil-fuel surplus for feed manufacturing, facility electricity and propane use, and completed-feed transport represented 52%, 39%, and 9%, respectively, of the total for the no-use scenario

5 Alternative-scenario results

5.1 Reduction in completed-feed transportation distance

When the completed-feed transportation distance was reduced by 61%, the greatest reduction of environmental impacts compared to the baseline scenarios occurred for ecotoxicity, with reductions ranging from 9.8–15.4%

Table 9 Summary of EcoIndicator 99 impacts with corresponding 95% confidence interval from the Monte Carlo sensitivity analysis of the five study sub-processes for no antimicrobial-use, CTC-use, and tylosin-use scenerios

	Climate change (DALY)	Acidification/(PDF m^2y)	Ecotoxicity (PAF m^2y)	Fossil fuel surplus (MJ surplus)
No antimicrobial use				
Feed manufacturing	7.98E−06±1.69E−07	1.11±0.01	0.40±0.13	51.72±0.68
Completed-feed transport	9.69E−07±5.11E−11	0.46±0.00	0.24±0.00	8.62±0.00
Electricity and propane use	3.46E−06±1.09E−07	0.55±0.01	0.15±0.13	40.29±0.84
Enteric and manure emissions	6.42E−06±6.66E−08	15.87±0.02	0.00	0.00
Antimicrobial Production	0.00E+00	0.00	0.00	0.00
Total	1.88E−05	17.99	0.79	100.63
CTC use				
Feed manufacturing	7.72E−06±1.72E−07	1.08±0.01	0.38±0.13	50.17±0.68
Completed-feed transport	9.40E−07±4.93E−11	0.45±0.00	0.23±0.00	8.37±0.00
Electricity and propane use	3.19E−06±1.08E−07	0.51±0.01	0.13±0.12	37.18±0.85
Enteric and manure emissions	6.41E−06±6.95E−08	15.87±0.02	0.00	0.00
Antimicrobial Production	5.66E−06±3.45E−07	0.73±0.02	0.44±0.36	6.13±5.69
Total	2.39E−05	18.63	1.20	101.85
Tylosin use				
Feed manufacturing	7.72E−06±1.66E−07	1.08±0.01	0.38±0.12	50.17±0.65
Completed-feed transport	9.47E−07±5.09E−11	0.45±0.00	0.24±0.00	8.42±0.00
Electricity and propane use	3.19E−06±1.08E−07	0.51±0.01	0.13±0.12	37.18±0.85
Enteric and manure emissions	6.42E−06±6.88E−08	15.87±0.02	0.00	0.00
Antimicrobial production	8.86E−06±3.46E−07	1.13±0.02	0.39±0.39	8.41±5.70
Total	2.71E−05	19.04	1.14	104.18

(Fig. 6). Not surprisingly, no antimicrobial use resulted in the greatest ecotoxicity benefit, since regional feed transport was the greatest contributor to this impact category. For CTC and tylosin, regional completed-feed transport only constituted about 6.3% of the total transportation burden, and thus changes in feed-transport distance influenced net ecotoxicity impacts only slightly. All scenarios had lower impacts associated with climate change, acidification and eutrophication, and fossil-fuel surplus, again with no antimicrobial use generally resulting in slightly lower impacts compared with CTC and tylosin use.

5.2 Reduction of antimicrobial use

A 50% reduction in antimicrobial dose throughout the swine life cycle resulted in considerable reductions in climate-change and ecotoxicity impacts for both CTC and tylosin use (Table 10 and Fig. 7). The greatest reduction in

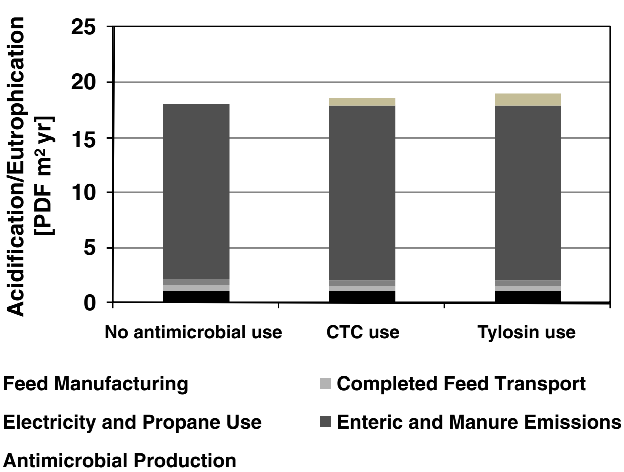

Fig. 3 Acidification and eutrophication impacts for the no antimicrobial-use, CTC-use, and tylosin-use scenarios

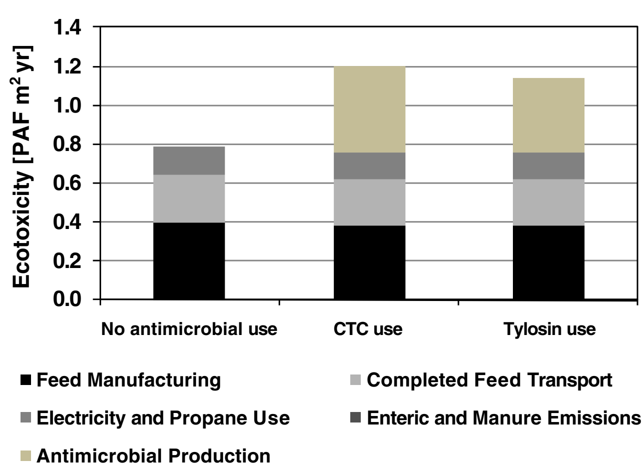

Fig. 4 Ecotoxicity impacts for the no antimicrobial-use, CTC-use, and tylosin-use scenarios

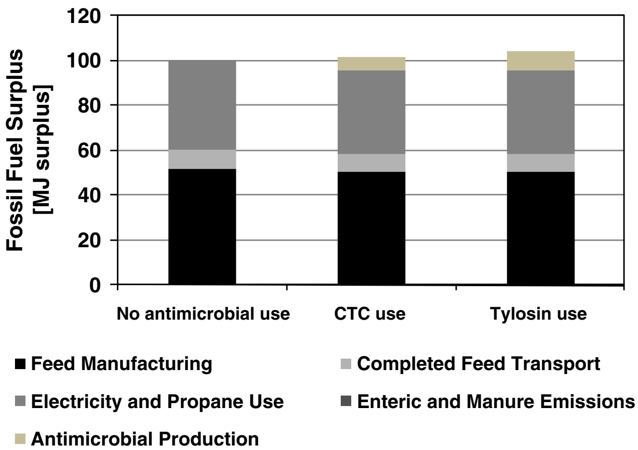

Fig. 5 Fossil fuel surplus for the no antimicrobial-use, CTC-use, and tylosin-use scenarios

climate-change impacts (15.3%) occurred for tylosin use (see Table 10), primarily due to the reduction in transport mileage associated with tylosin (tylosin is shipped 1,145 km compared with 370 km for CTC) and the net higher dose requirement of tylosin compared to CTC. Ecotoxicity impacts also were reduced between 15.9% and 17.5% for the antimicrobial compounds.

5.3 Average US energy allocation

By changing the energy profile of the feed manufacturing and production facilities to one using the average US energy portfolio (US-EIA 2010), environmental impacts of all alternative scenarios increased compared with baseline scenarios, regardless of whether or not antimicrobials were used (Fig. 8). The increased reliance on coal-fired energy in the US average portfolio, compared to that for South Dakota (see Table 5) was the primary basis of these increased impacts. Coal-fired energy is known to be a large source of heavy-metal emissions, and those increased emissions resulted in greater ecotoxicity impact for all of the alternative scenarios, especially for the no antimicrobial-use scenario, in which ecotoxicity increased 17.5%. CTC and tylosin use also resulted in increased ecotoxicity; however, the magnitude of the no antimicrobial-use impacts was greater due to the longer swine residence time within the production facility (requiring additional energy for the life-cycle duration) and the greater feed volume required per head of swine.

6 Discussion

Although feed production was not included within the framework of this study, its inclusion would be expected to increase climate-change impacts significantly for all scenarios, as reported by Erikkson et al. (2005). In their study, production of soybeans, peas (*Pisum sativum*), wheat (*Triticum aestivum*), and barley (*Hordeum vulgare*) for feed for Swedish swine production was consistently the greatest contributor to global-warming potential for their swine-production model. The importance of feed for animal production has also been reported by Dalgaard et al. (2007) (Danish swine) and Peters et al. (2010) (Australian beef). If our study was to include the common feed-mix used for most US NGP swine-production facilities (Table 3), we would expect the relative magnitude of climate-change impacts associated with feed production for both CTC and

Fig. 6 Scenario-analysis results for a reduction in completed-feed transportation distance of 61%. Percent impact reductions represent changes in EcoIndicator 99 environmental impacts as compared to those of baseline scenarios

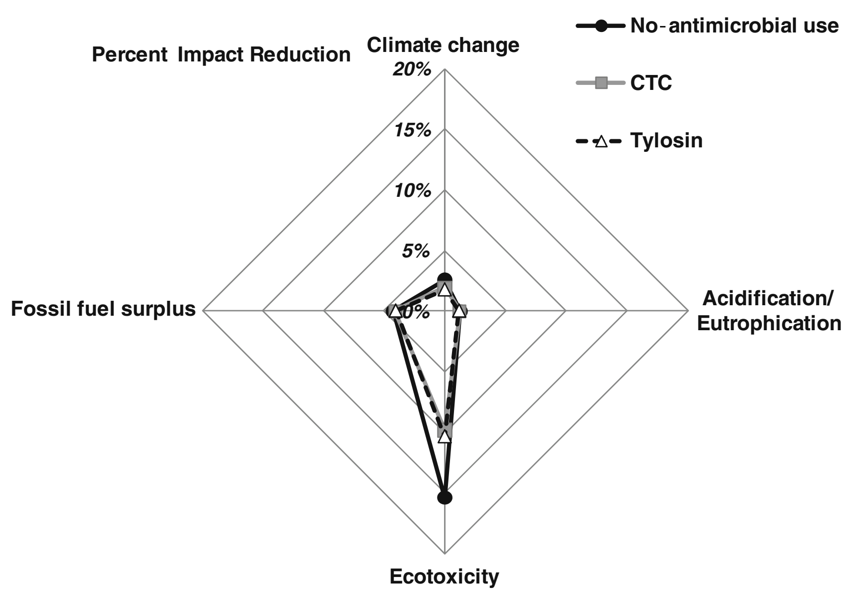

Table 10 Summary of scenario-analysis EcoIndicator 99 environmental impact results for the 50% reduction in antimicrobial-dose effects as compared with the no antimicrobial-use scenario results. Baseline values signify corresponding impacts determined for full-antimicrobial-dose scenarios

Impact category	Unit	No antimicrobial use	Baseline	CTC use 50% use reduction	% reduction	Baseline	Tylosin use 50% use reduction	% reduction
Climate change	DALY	1.88E−05	2.39E−05	2.14E−05	10.7%	2.71E−05	2.30E−05	15.3%
Acidification/ Eutrophication	PDF m^2y	17.99	18.63	18.30	1.7%	19.04	18.51	2.8%
Ecotoxicity	PAF m^2y	0.79	1.20	0.99	17.5%	1.14	0.96	15.9%
Fossil fuel surplus	MJ surplus	100.63	101.85	101.12	0.7%	104.18	102.31	1.8%

tylosin use to be significantly less than those of Eriksson et al. (2005) due to the increased feed-utilization efficiency associated with antimicrobial use. The influence of feed production, including processes such as synthetic fertilizer production, irrigation water use, transport emissions, and field nitrogen emissions, would have expectantly greater contributions towards climate-change impacts, thus any process that results in less feed demand would have beneficial climate-change consequences.

For acidification impacts, Eriksson et al. (2005) reported that 99% of acidification impacts were due to ammonia emissions associated with the swine-rearing phases. The authors suggest ammonia emissions could be reduced either by minimizing NH_3 excretion, using low-emission techniques for manure storage and spreading, or avoiding overfeeding of crude protein (such as peas, soybeans, and synthetic amino acids), which had significantly higher net acidification impacts than more traditional feed ingredients such as barley, wheat, and canola (*Brassica napus*). Dalgaard et al. (2007) also reported a high contribution of ammonia (84%), with production housing resulting in the highest acidification potential during swine production. It should be noted that impacts reported by Eriksson et al. (2005) were based upon local conditions reported for Sweden and do not necessarily reflect common agricultural practices employed in the USA. For example, the high acidification impact reported for soybeans in Sweden was attributed to the long-distance transportation required, while soybean production in the US NGP. is quite common, with many swine-production facilities specifically located adjacent to feed-production sites.

The ecotoxicity impacts for tylosin use may be attributed to the increased dependence on coal power during tylosin manufacturing (see Table 2) and greater transport distance from the manufacturing location to the point of use (see Table 1), both resulting in large increases in the net release of heavy metals into the environment. These impacts may be decreased by minimizing the reliance on coal as the primary energy source and instead utilizing a higher percentage of renewable-energy sources required for manufacturing. Furthermore, relocating the manufacturing site closer to the product-use location would be expected to reduce ecotoxicity of antimicrobial use.

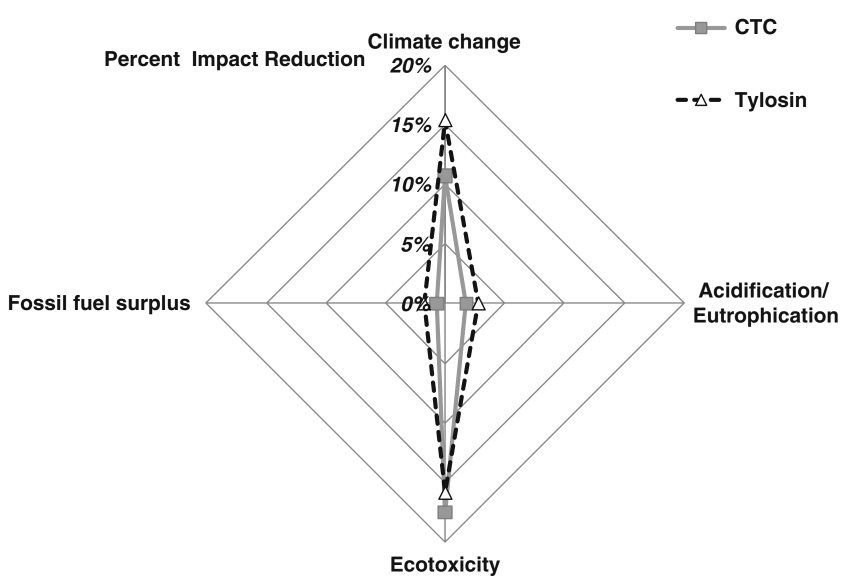

Fig. 7 Scenario-analysis results for a 50% reduction in antimicrobial doses. Percent impact reductions represent changes in EcoIndicator 99 environmental impacts as compared with those of the two baseline scenarios with antimicrobial use

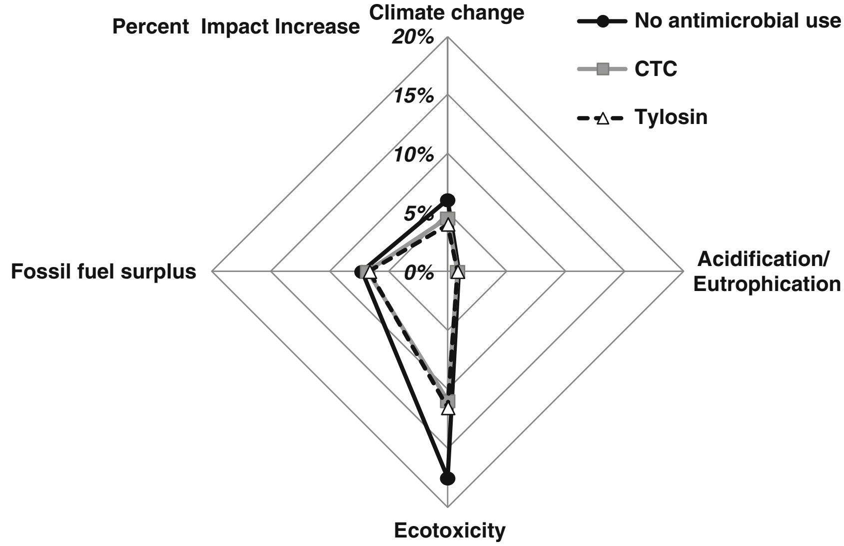

Fig. 8 Scenario-analysis results for using the average US energy portfolio (US-EIA 2010) for feed-manufacturing and production-facility operations. Percent impact increases represent changes in EcoIndicator 99 environmental impacts as compared with those of the baseline scenarios, which used the average South Dakota energy portfolio

It is important to note that for the four impacts evaluated, none of the total impact reductions associated with a 50% reduction in antimicrobial use resulted in an impact score below that of the no antimicrobial-use scenario (see Table 9). Thus, even halving the dose of CTC or tylosin does not appear to have lower environmental impacts than those of a production facility not using antimicrobial compounds when considering the system boundaries of this study. Again, feedstuff production associated impacts would likely increase due to the subsequent reduction in feed-utilization efficiencies expected with reduced antimicrobial doses.

While intrinsic benefits associated with administering antimicrobials such as increased feed utilization and faster time to reach market weight exist, when considering the average US energy profile that is heavily dependent on coal-fired power, there appears to be no significant LCA environmental benefit for antimicrobial use. Producers could obtain tangible benefits, however, if they were to carefully and selectively implement renewable-energy resources to meet facility power-requirements. Further benefits also could be achieved by augmenting additional renewable-energy resources within the antimicrobial manufacturing and transportation phases and considering use of rail transport.

7 Conclusions and perspectives

Administering sub-therapeutic levels of antimicrobial compounds CTC and tylosin within the US swine-production industry has become integral to the animal-food industry (Sarmah et al. 2006), providing producers with many tangible benefits for meeting the increasing demands of today's swine marketplace. "Greening" pressures in this marketplace, however, are requiring swine producers to scrutinize their environmental footprint with respect to GHG emissions, land use, and facility operations to meet both consumer demands and legislative mandates. While antimicrobial use provides many local benefits for producers such as improved growth rate and efficiency of feed utilization, reduction of mortality and morbidity, and disease prevention (Cromwell 2002), ancillary environmental burdens associated with antimicrobial use were not considered within this study framework, such as those associated with manure-handling and land-application processes. Results from this study suggest that swine producers should consider carefully both the benefits of continuous antimicrobial use with the environmental burdens outlined herein and those from other use-related studies. Our results demonstrate that antimicrobial manufacturing and use associated with a typical US NGP swine-production facility increases all EcoIndicator 99 environmental impacts (climate change, acidification and eutrophication, ecotoxicity, and fossil-fuel surplus) compared to a facility that does not use these compounds. These increased environmental impacts may be lessened, although not entirely eliminated, through implementation of additional renewable-energy resources globally within the antimicrobial manufacturing and transportation sectors, and locally within the swine producers' facility operations. Furthermore, local benefits could be provided through reducing the transportation distances associated with feed and antimicrobial distribution (i.e., using local sources). Future studies incorporating specific US feed-production processes, including impacts and benefits associated with the growing practice of ethanol distillers grain feed incorporation, is needed to further understand the complete life cycle of antimicrobial use within swine production.

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